AUTOMATION & CONTROL INSTITUTE
INSTITUT FÜR AUTOMATISIERUNGS- & REGELUNGSTECHNIK

TECHNISCHE UNIVERSITÄT WIEN

Optimal Design of Baking Plates for an Inductive Wafer Baking Oven

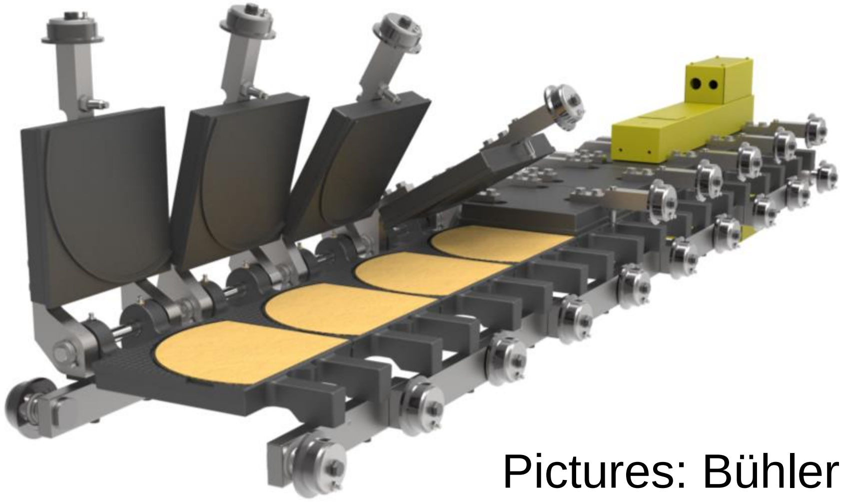
Johannes STEINBACH, Lukas JADACHOWSKI, Andreas KUGI, Andreas STEINBOECK

COMSOL Conference

Munich, October 2023

Agenda

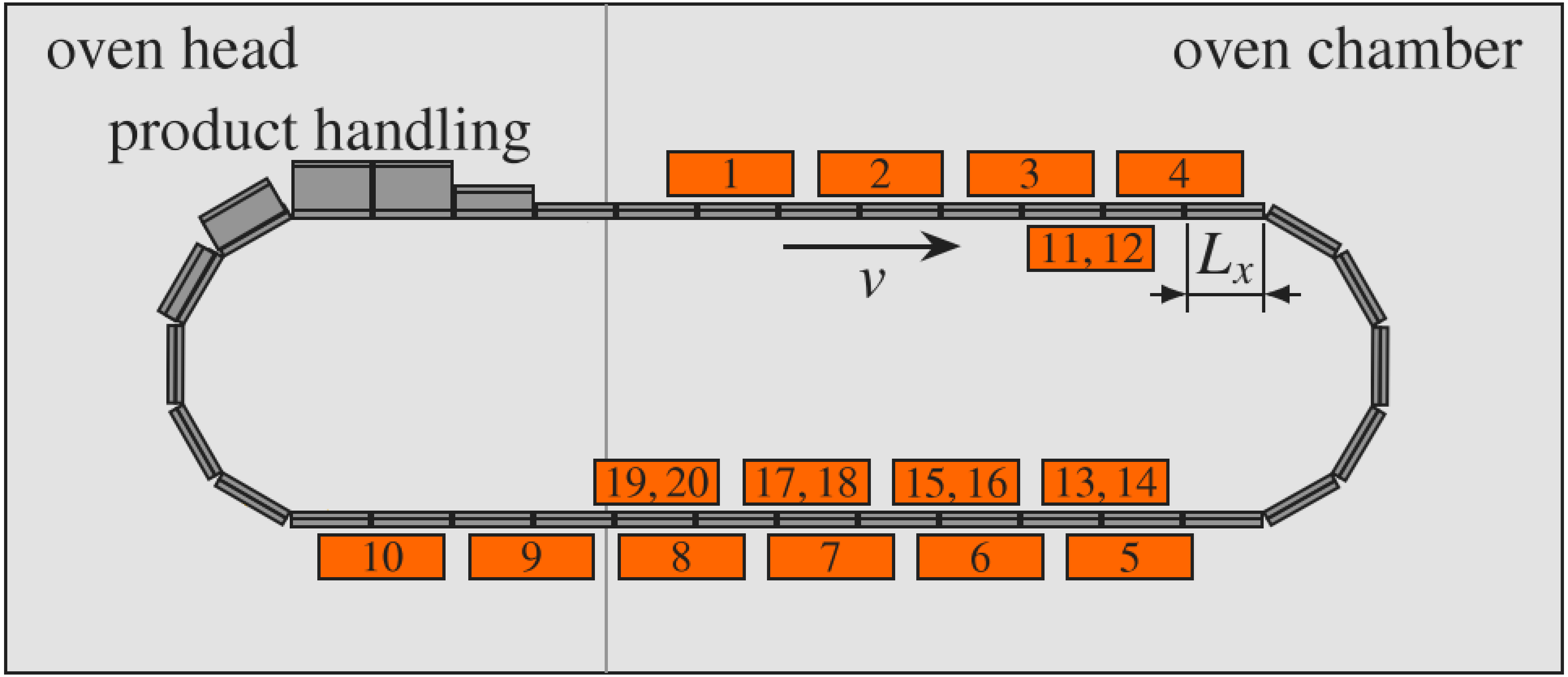
- **Motivation and Overview**
- Simulation Setup
- Optimization Problem
- Conclusion and Outlook



Pictures: Bühler

Overview – Industrial Wafer Production

- initially liquid batter is baked between two metallic baking plates
- baking plate pairs pass heaters which supply the necessary thermal power



J. Steinbach, L. Jadachowski, A. Steinboeck, and A. Kugi (2023). Modeling and observer design of an inductive oven with continuous product flow. Mechatronics (95) 103041

Motivation

State of the Art

- gas-fired ovens with SISO control structure
- drawbacks: low energy efficiency, flue gas contact, and slow return to desired operating state after interruptions

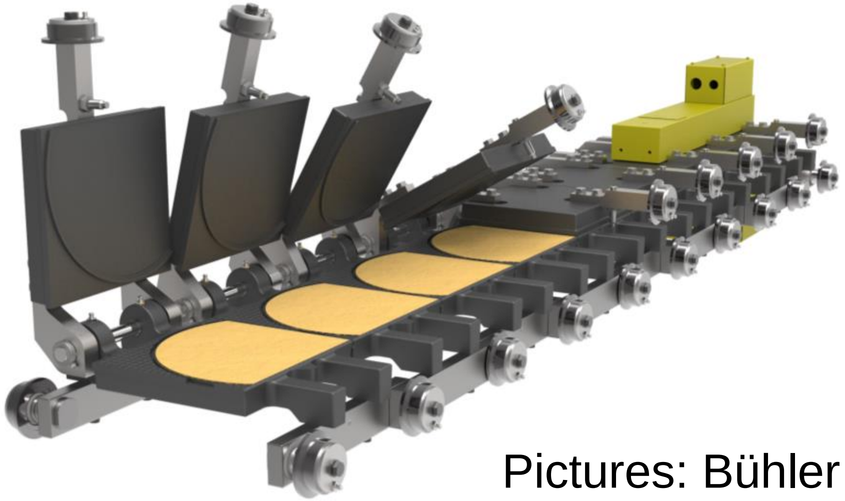
Project Goals

- transition to inductive heating
- model-based control and optimization of the baking plate thickness
- systematic consideration of several design objectives

Agenda

ACIN

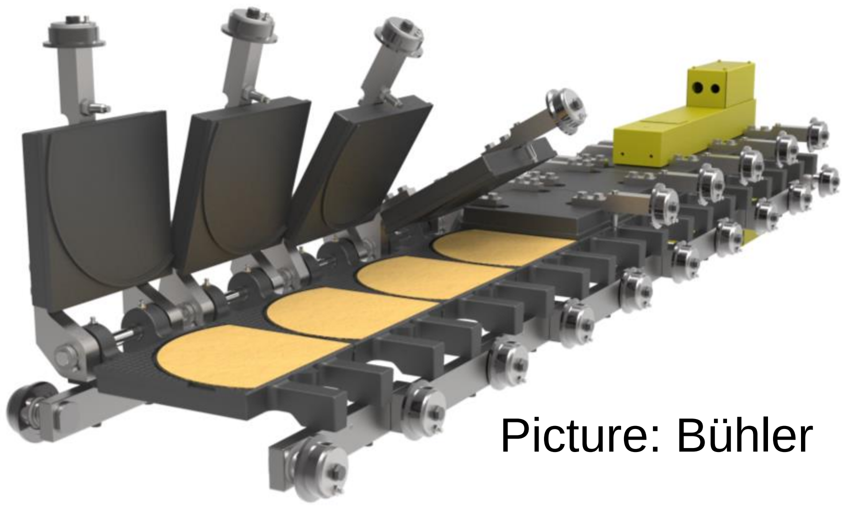
- Motivation and Overview
- **Simulation Setup**
- Optimization Problem
- Conclusion and Outlook



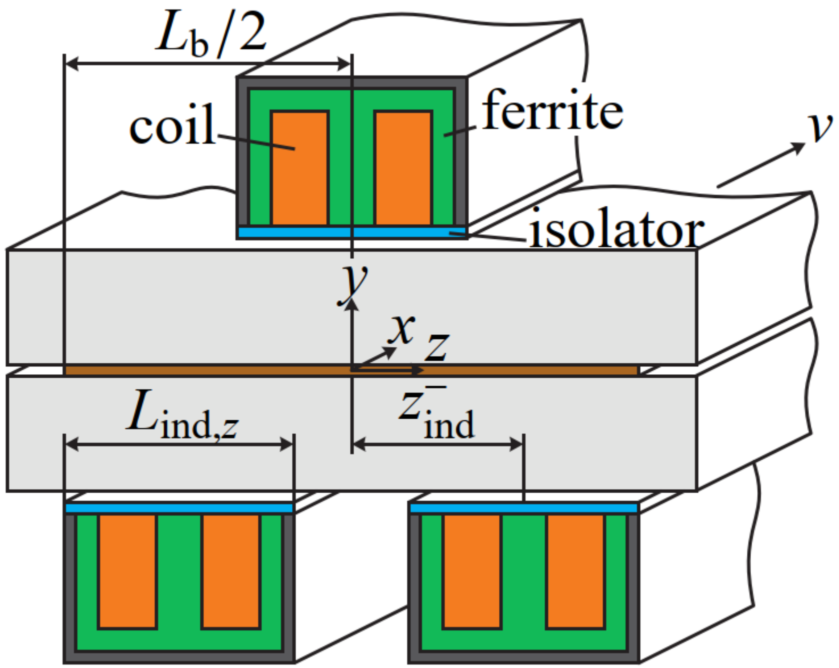
Pictures: Bühler

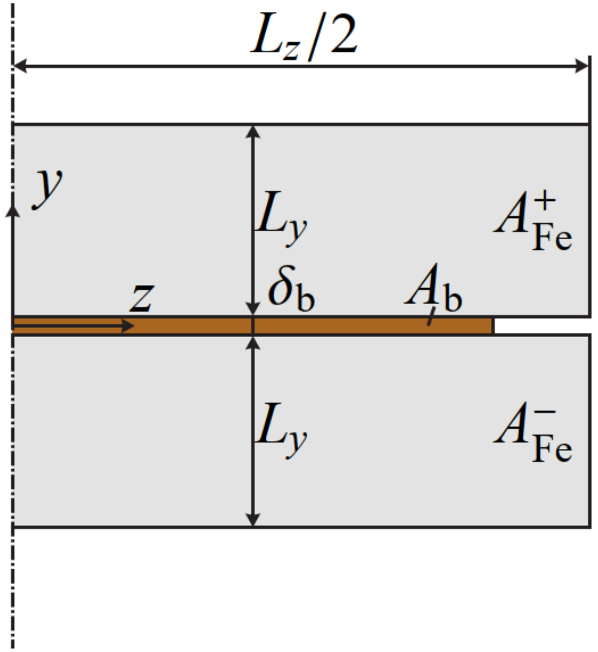
Simulation Setup

- 2D cross-section perpendicular to direction of motion
- use symmetry: simulate only positive z-axis
- computational domain: $A_{\mathrm{Fe}}^{-} \cup A_{\mathrm{Fe}}^{+} \cup A_{\mathrm{b}}$
- based on previous simulations for inductive heating
- solved with COMSOL
- $\rho c_{\mathrm{p}} \frac{\partial T}{\partial t} = \lambda \left(\frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + Q$
  initial condition, $T|_{t=0} = T_0$
  and boundary conditions
  $-n_y \lambda \frac{\partial T}{\partial y} - n_z \lambda \frac{\partial T}{\partial z} = q_n$



Picture: Bühler





Inductive Heat Sources

Difficulties

- appropriate mesh sizes for electromagnetic and thermal simulations differ widely
- coupled simulations increase computational load
  - but: coupling from thermal phenomena to electromagnetics is small

Solutions

- assume negligible change of electromagnetic properties over temperature
- use electromagnetic simulations to find spatial distribution of inductive heat Q
  - in y-direction: aligns with theory (exponential decay; penetration depth δ_{E})

Inductive Heat Sources – Spatial Characteristics

- source term Q in upper baking plates:

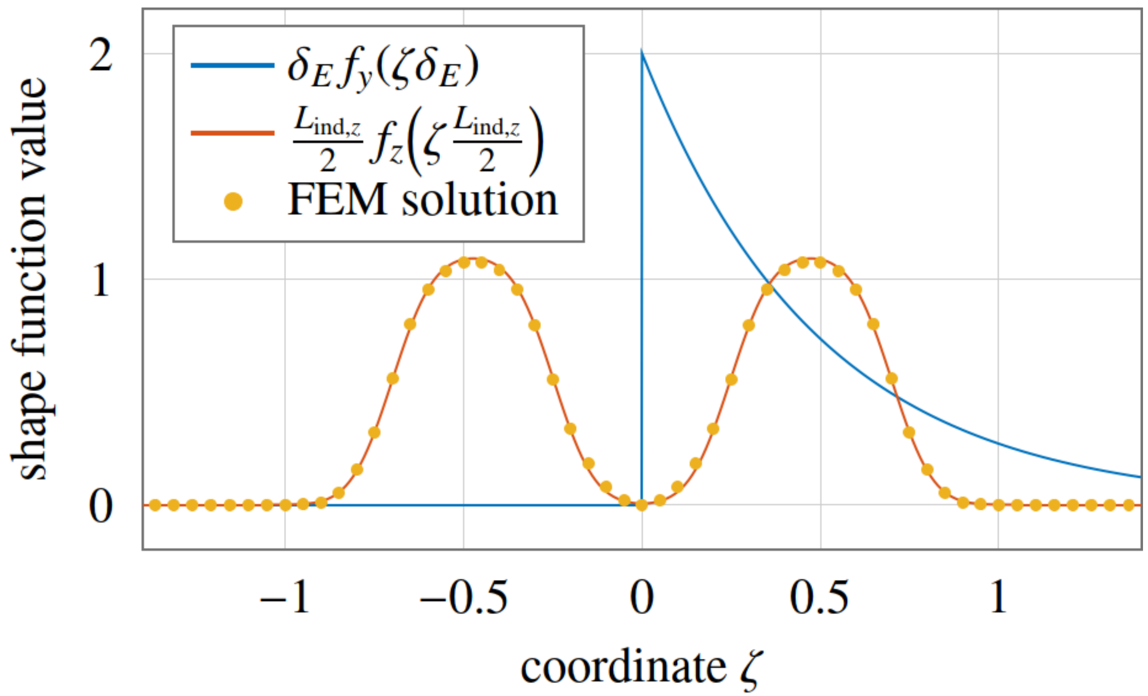
$$Q(y,z,t) = P_+(t)\frac{1}{L_+} f_y\left(L_y + \frac{\delta_b}{2} - y\right) f_z(z)$$

- source term Q in lower baking plates:

$$Q(y,z,t) = P_-(t)\frac{1}{L_-} f_y\left(L_y + \frac{\delta_b}{2} + y\right) f_z(z - z_{\text{ind}}^-)$$

- $f_y(y) = \begin{cases} \frac{2}{\delta_E} e^{-2y/\delta_E} & y > 0 \\ 0 & y \leq 0 \end{cases}, \qquad \delta_E = \sqrt{\frac{\rho_E}{\mu_E \pi f}}$

- $f_z(z) = a\big(\operatorname{erf}(b|z| - c) - \operatorname{erf}(b|z| - d)\big)$

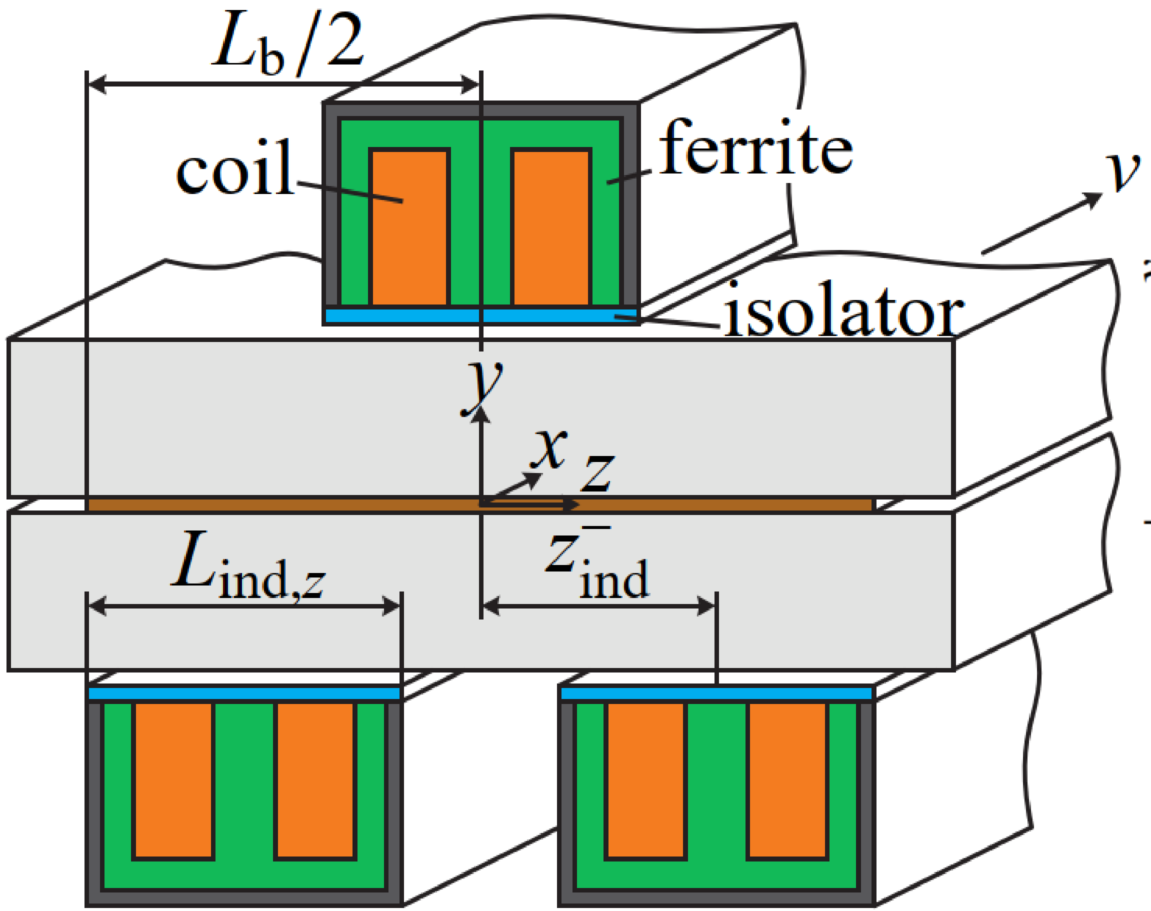


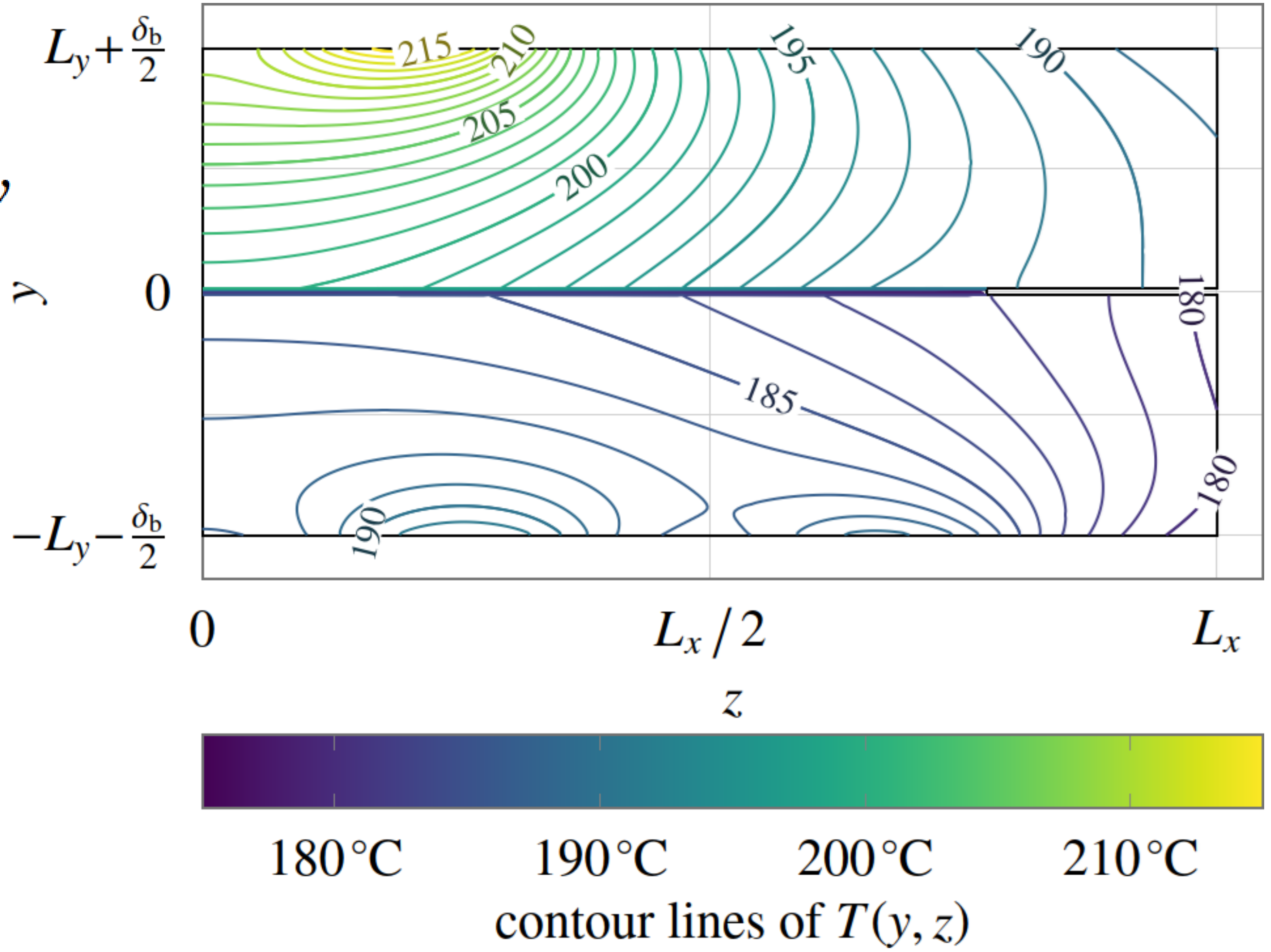
Simulation Overview

- simulation studies A, B, C
- nonlinear baking process model includes $c_{\mathrm{p}}(T)$, linear model uses energy balance and constant c_{p} instead

Simulation A	Simulation B	Simulation C
steady-state simulation	time-dependent simulation	time-dependent simulation
cycle-averaged quantities	nonlinear baking process model	linear baking process model
spatial temperature variation	temporal temperature variation	temporal temperature variation
fast, fine discretization possible	computationally intensive	moderately intensive computations
Recommendations		
extensive use possible	use for validation only	few simulations for start-up time

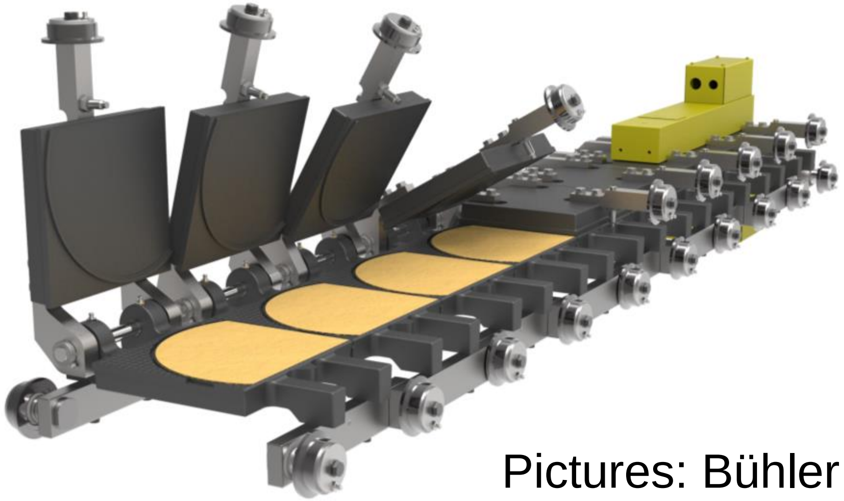
Steady-State Temperature Field





Agenda

- Motivation and Overview
- Simulation Setup
- **Optimization Problem**
- Conclusion and Outlook



Pictures: Bühler

Optimization Problem – Cost Function

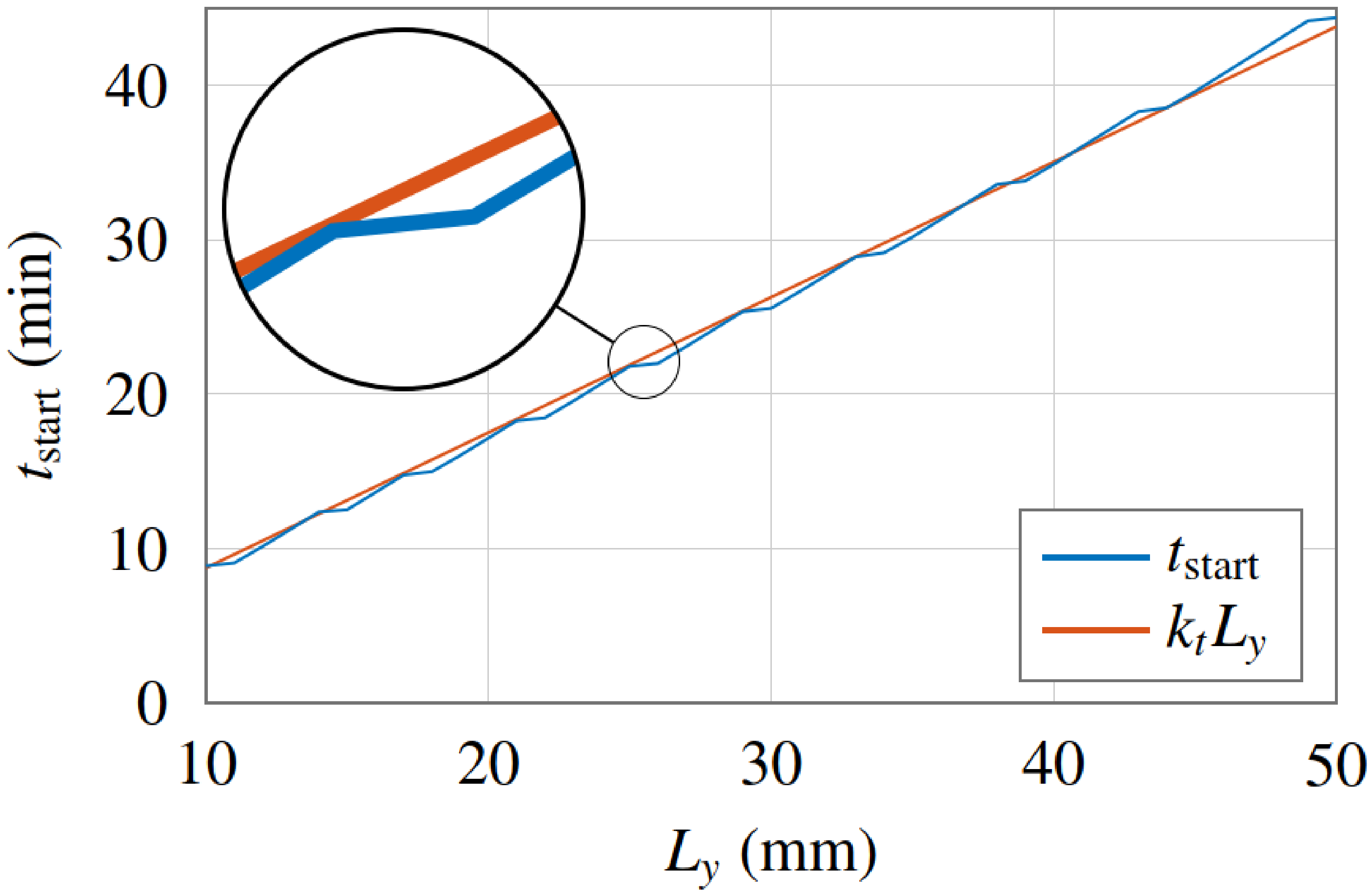
ACIN

- antagonistic objectives: fast start-up time vs. good (temporal and spatial) homogeneity of temperature at the baking face
- minimize objective function $C(L_y) = C_t t_{\mathrm{start}}(L_y) + C_{T,t} T_{\Delta,\mathrm{t}}(L_y) + C_{T,z} T_{\Delta,\mathrm{z}}(L_y)$
- start-up time t_{start} and temporal temperature variation $T_{\Delta,\mathrm{t}}$ from transient simulations B, C
- spatial temperature variation $T_{\Delta,\mathrm{z}}$ from steady-state simulation A

- finding the minimum requires many computationally expensive simulations
  - circumvented by minimizing surrogate cost function $C_s(L_y) \approx C(L_y)$

Optimization Problem – Start-up Time

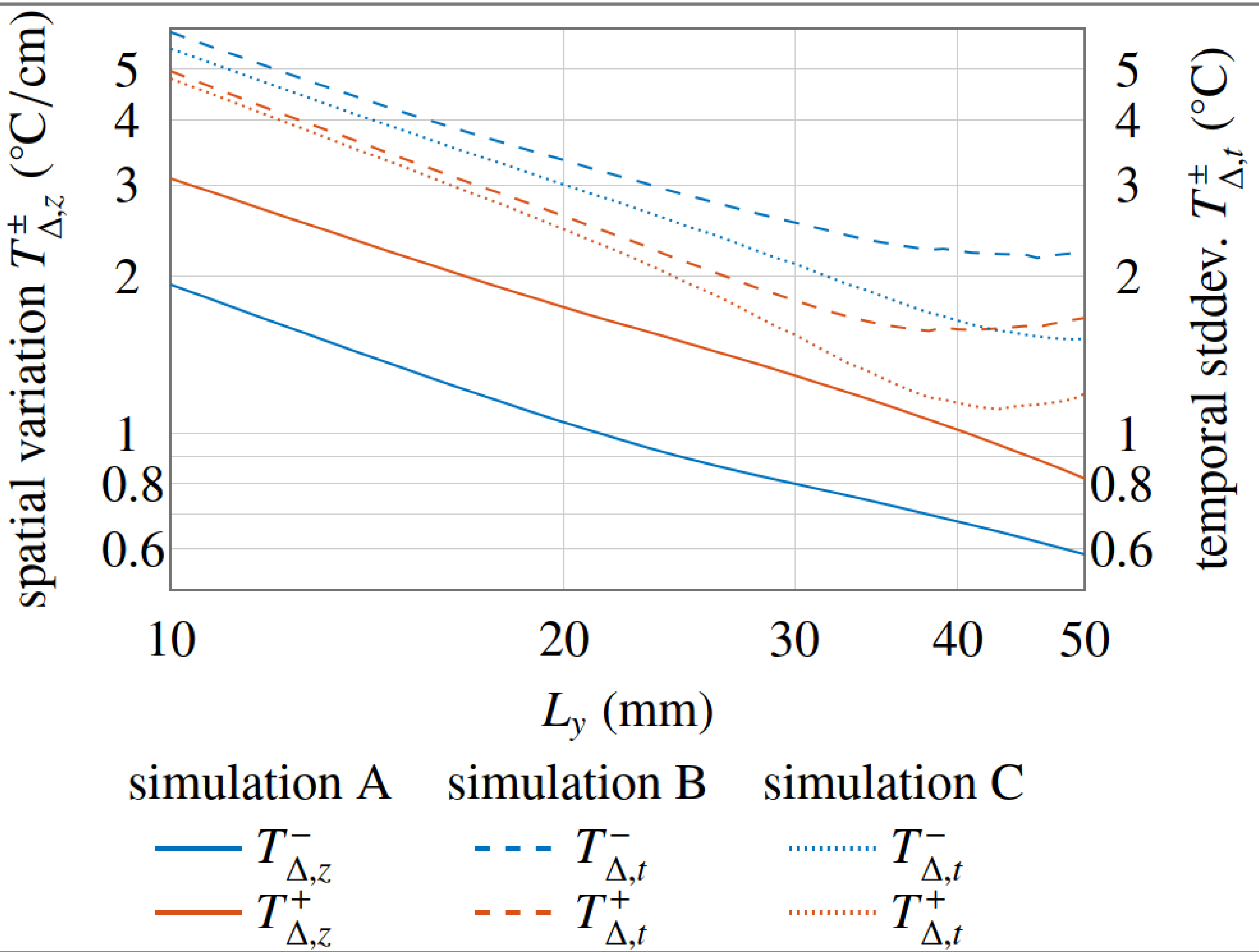
- minimum time for heating from ambient temperature to baking temperature
- approximately linear in the baking plate thickness
- inductive heat is not distributed evenly along the path through the oven, hence the nonsmooth shape



Optimization Problem – Temperature Variation

ACIN

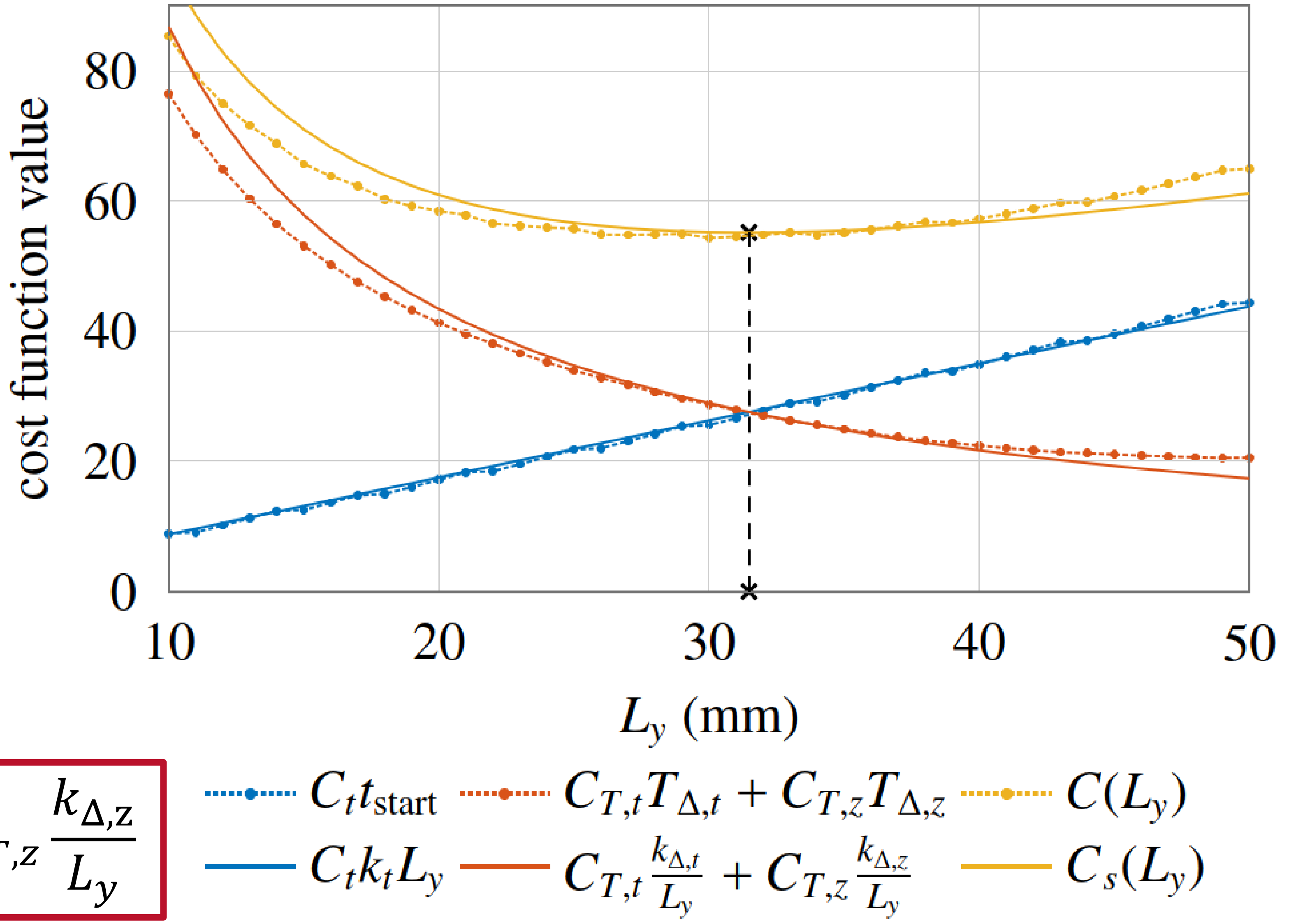
- spatial variation: mean absolute gradient magnitude $T^{\pm}_{\Delta,z}$ at the baking face
- temporal variation: temporal standard deviation $T^{\pm}_{\Delta,t}$ of baking face temperature
- both show proportionality to $1/L_y$ over a wide range of L_y



Optimization Problem – Solution

ACIN

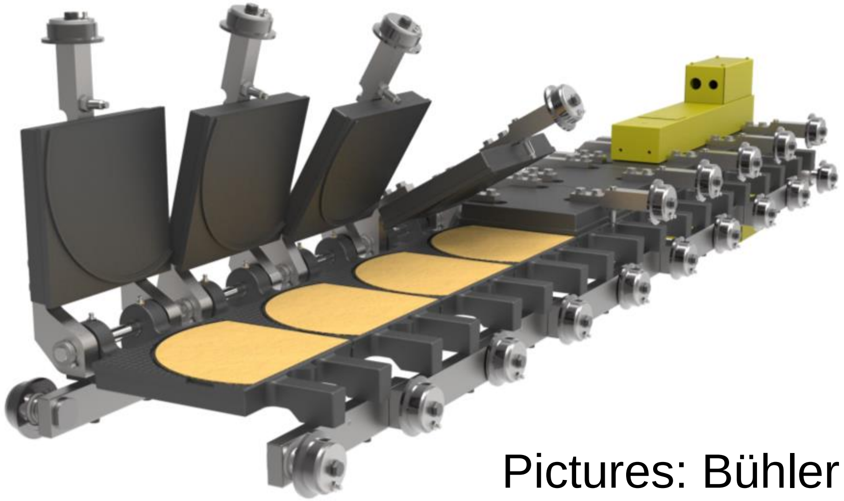
- surrogate function based on
  $t_{\text{start}} \approx k_t L_y$
  $T_{\Delta,\text{t}} = T^+_{\Delta,\text{t}} + T^-_{\Delta,\text{t}} \approx \frac{k_{\Delta,t}}{L_y}$
  $T_{\Delta,\text{z}} = T^+_{\Delta,\text{z}} + T^-_{\Delta,\text{z}} \approx \frac{k_{\Delta,\text{z}}}{L_y}$
- weights $C_t = 1\,\frac{1}{\text{min}}$,
  $C_{T,t} = 5\,\frac{1}{°\text{C}}$ and $C_{T,z} = 5\,\frac{\text{cm}}{°\text{C}}$



$$C_s(L_y) = C_t k_t L_y + C_{T,t} \frac{k_{\Delta,\text{t}}}{L_y} + C_{T,z} \frac{k_{\Delta,\text{z}}}{L_y}$$

Agenda

- Motivation and Overview
- Simulation Setup
- Optimization Problem
- **Conclusion and Outlook**



Pictures: Bühler

Conclusion and Outlook

Conclusion

- demanding problem was reduced to a thermal simulation
  - inductive subsystem replaced by distributed heat source
- simplified optimization problem
  - easily computable minimum of the surrogate cost function

Outlook

- industrial application of optimized baking plate thickness
- transfer to different baking plate types